The Effects of Solder Joint Rework on Plated-Through Holes in Multilayer Printed Wiring Boards

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1.0 Abstract

In printed wiring assemblies (PWA) the plated through hole (PTH) as an interconnect structure is particularly sensitive to damage. This study was conducted to determine the effects on PTHs when there is repeated rework of solder joints on multilayer PWBs. NASA flight qualified PWBs and NASA trained and certified operators in high reliability hand soldering and rework methods were used in this study.

Statistical analysis was employed to interpret the results of the study, and to extrapolate the data in calculating the estimated significance of the variables used. Finite Element Analysis (FEA) was employed to verify the thermal characteristics of the PTH structure and to determine the areas of highest stress.

An understanding of how much rework is too much rework will continue to become increasingly critical as board real estate mandates continued process evaluation to improve reliability.

2.0 Objective

The objective of this study was to evaluate the effects of repeated rework on solder joints and the degradation to the PTH structure in relationship to the board material, the soldering iron temperature, the thickness of the dielectric, and the operator. The study also evaluates which parameter was more significant to the PTH degradation.

3.0 Introduction

Controlling the amount of solder joint rework is essential to the enhanced reliability of NASA's space-flight hardware. The plated-through hole is a good example of a PCB structure which can be damaged significantly during the assembly process if care is not taken in the PTH/PCB design. In addition, the thermal cycle characteristics used to attach the components to the board also can impact negatively on PTH reliability.[1]

This study was conducted to determine how many reworks a solder joint can undergo before a failure mechanism is introduced in the PTH structure or the PWB circuitry. To accomplish this study, sixteen boards underwent nine rework cycles. Parts were soldered on the PWB and then desoldered and removed. The PWBs were visually inspected for damage, and microsectioned after the fifth heat cycle. This process continued until the PWB completed nine heat cycles of soldering or desoldering.

4.0 Methodology

[1]Iannuzzelli, Raymond J., "Effects of PCB Manufacturing on Plated-Through Hole Reliability", Electronic Manufacturing, p. 18, (May 1989)

The study was conducted in three distinct phases. The first phase consisted of manufacturing sixteen PWAs through nine consecutive heat cycles (one heat cycle consists of either soldering parts on the PWA or desoldering and removing the parts). The second phase, as addressed in section 5.0 of this paper, consisted of statistical analysis of the data collected in phase one to determine the significance of the variables used. The third phase, as addressed in section 6.0 of this paper, involved FEA of the PTH structure to identify the areas of highest stress.

Manufacturing
Flight qualified PWBs and parts were procured and visually inspected. The PWBs were compliant with MIL-P-55110. The operators were selected and sent for the applicable training at the NASA Training Center. All PWAs were demoisturized prior to soldering and the materials used (solder, flux, soldering irons, etc.) were in accordance with NHB 5300.4(3A-2). All parts and PWBs were stored in a moisture-free environment.

A matrix was developed designating the variable assignments. There were eight PWAs reworked per run, with two runs, for a total of sixteen PWAs. All manufacturing of the boards was done according to the following matrix:

TRIALS (PWA)	OPERATOR	BOARD MATERIAL	BOARD LAYERS	IRON TEMP.
1	2	GI (polyimide)	10	600°F
2	1	GI	4	700°F
3	2	FR-4 (epoxy)	4	600°F
4	1	FR-4	10	700°F
5	1	FR-4	4	600°F
6	2	FR-4	10	700°F
7	1	GI	10	600°F
8	2	GI	4	700°F

In order to determine the point at which defects were likely to be detected, a test board was prepared. The entire test board was populated and underwent 10 consecutive heat cycles. After each heat cycle, the PWA was microsectioned and analyzed. No defects were noted until after the seventh application of heat. At this point it was determined to preform visual inspections after each heat cycle and to microsection the PWAs after the fifth heat cycle noting the observation of any failure mechanisms in the PTH structure (see Figure 1 for a flow diagram of the process).

Each of the sixteen PWAs underwent nine heat cycles with the operators noting defects observed at the visual inpections. After the fifth heat cycle each PWA was microsectioned with a failure analysis engineer noting any defects to the sample. There PWAs were inspected for four defect types: trace to barrel separation, lifted lands, barrel cracks, and laminate voids.

4.1 Identifying the Process Variables

A. Operator. Two operators were utilized through out the study. Both operators were trained and certified at a NASA Training Center for high reliability hand soldering to NHB 5300.4(3A-2), and rework and repair methods for PWBs. One operator was experienced while the second operator was inexperienced.

B. Iron Temperature. Two soldering iron temperatures were used.
1. 600° F, 315° C
2. 700° F, 371° C

C. Board Material. The two primary types of PWB material used for space-flight hardware are polyimide (GI) and epoxy glass (FR-4). These two board materials were used in the study.

D. Dielectric Thickness. Ten layer boards with an approximate dielectric thickness of .008 inches, and four layer boards with an approximate dielectric thickness of .027 inches were used.

4.2 Assumptions/Evaluation of Assumptions

A. After the preparation of the test PWA, it was determined the PWAs would be visually inspected for damage through out the process, and microsectioned for structural analysis from the fifth heat cycle through the ninth heat cycle. It is assumed the defects occurred in the heat cycle in which they were observed.

B. The defects noted are not necessarily catastrophic failures as opposed to an induced failure mechanism.

4.3 Results

In all fifty-nine defects were observed. It should be noted there were no catastrophic failures, but the indication of a failure mechanism. The distribution of defects were as follows:

Trace to barrel separation - 33 observations (56% of total defects)
Lifted lands - 25 (42% of total defects)
Barel cracks - 1 (2% of total defects)
Laminate voids - 0

The following two tables were the test results of the experiment showing the number of defects observed in each heat cycle. The number of defects were the cummulative number of defects observed in each rework cycle.

PWA Set #1

	Cycle 1	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**	**Cycle 6**	**Cycle 7**	**Cycle 8**	**Cycle 9**
Board 1	0	0	0	0	0	0	0	2	3
Board 2	0	0	0	0	0	0	0	0	0
Board 3	0	0	0	0	0	0	0	0	0
Board 4	0	0	0	0	0	0	1	1	5
Board 5	0	0	0	0	0	0	0	0	0
Board 6	0	0	0	0	0	1	3	3	3
Board 7	0	0	0	0	2	2	5	5	7
Board 8	0	0	0	0	0	0	0	0	0

PWA Set #2

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9
Board 1	0	0	0	0	12	12	12	12	12
Board 2	0	0	0	0	1	1	1	1	1
Board 3	0	0	0	0	1	2	3	3	4
Board 4	0	0	0	0	6	8	9	10	10
Board 5	0	0	0	0	1	1	1	4	4
Board 6	0	0	0	0	0	1	3	5	10
Board 7	0	0	0	0	0	0	0	0	0
Board 8	0	0	0	0	0	0	0	0	0

4.4 Discussion

The first notable observation was that all PWAs showed no defects until after the fourth heat cycle. The results also showed the most significant variable was the dielectric thickness. In both runs the ten layer PWAs had more defects than the four layer PWAs. Without further analysis, no more observations could be made.

Throught out the course of the experiment it was found that the operator as a variable could not be defined as experienced or inexperienced. By the conclusion of the experiment, both operators were experienced and performing equally.

5.0 Statistical Analysis

The objective of this numerical analysis is to derive an estimating equation from observed defects. Four variables were evaluated to identify the most significant contributor to the number of defects. The four variables were operator's experience, board material, number of layers of board, and soldering iron temperature. Each variable has two levels as shown in the following :

	Level 1	**Level 2**
Operator	1 (experienced)	2 (inexperienced)
Board Material	FR4	GI
Dielectric Thickness	4 layers	10 layers
Temperature	600° F	700° F

For cost reduction, the fractional factorial method was used. Eight out of sixteen combinations of test conditions were used on two sets of eight boards. The following were the test conditions used:

	Operator	Board Material	Board Thickness	Temperature
Board 1	2	GI	10	600° F
Board 2	1	GI	4	700° F
Board 3	2	FR4	4	600° F
Board 4	1	FR4	10	700° F
Board 5	1	FR4	4	600° F
Board 6	2	FR4	10	700° F
Board 7	1	GI	10	600° F
Board 8	2	GI	4	700° F

When fitting a first order equation to a factorial experiment where each variable has only two levels, it is customary to "code" the independent variables with -1 representing the low level of a variable and +1 for the high level. The test condition matrix was as follows:

	Operator	Board Material	Board Thickness	Temperature
Board 1	1	1	1	-1
Board 2	-1	1	-1	1
Board 3	1	-1	-1	-1
Board 4	-1	-1	1	1
Board 5	-1	-1	-1	-1
Board 6	1	-1	1	1
Board 7	-1	1	1	-1
Board 8	1	1	-1	1

The Least Square Fit method was used to find the equation that best fit the test data. Since all variables were uncorrelated and there were only two levels per variable, the equation does not contain any quadratic or interacted terms. The equation was in the form:

$$Y=\beta_0 + \beta_1(\text{operator}) + \beta_2(\text{board material}) + \beta_3(\text{board thickness}) + \beta_4(\text{temperature})$$

where Y = number of defects
β_1, β_2, β_3, and β_4 are the coefficients of the variables.
β_0 = constant

By using a matrix calculation, the above model can be written in the form of $y = X\beta$.

$$y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{bmatrix} \qquad X = \begin{bmatrix} 1 & x_{11} & x_{21} & x_{31} & x_{41} \\ 1 & x_{12} & x_{22} & x_{32} & x_{42} \\ 1 & x_{13} & x_{23} & x_{33} & x_{43} \\ 1 & x_{14} & x_{24} & x_{34} & x_{44} \\ 1 & x_{15} & x_{25} & x_{35} & x_{45} \\ 1 & x_{16} & x_{26} & x_{36} & x_{46} \\ 1 & x_{17} & x_{27} & x_{37} & x_{47} \\ 1 & x_{18} & x_{28} & x_{38} & x_{48} \end{bmatrix}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix}$$ Coefficient Matrix

Using the test results from each rework cycle and fitting them into the equation by the method of least square fit, the following coeffficients were found:

Coefficients of Set #1

	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9

β_0	0.25	0.375	1.125	1.375	2.25
β_1	-0.25	-0.125	-0.375	-0.125	-0.75
β_2	0.25	0.125	0.125	0.375	0.25
β_3	0.25	0.375	1.125	1.375	2.25
β_4	-0.25	-0.125	-0.125	-0.375	-.0.25

Coefficients of Set #2

	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9
β_0	2.625	3.125	3.625	4.375	5.125
β_1	0.625	0.625	0.875	0.625	1.375
β_2	0.625	0.125	-0.375	-1.125	-1.875
β_3	1.875	2.125	2.375	2.375	2.875
β_4	-0.875	-0.625	-0.375	-0.375	0.125

To determine which variable contributed most significantly to the regression, we took the ratio of its mean square to the remainder mean square and compared the ratio for the different coefficients. The size of the ratio indicates the contribution of the variable to the total number of defects observed.

Ratio of the mean square to the remainder mean square on Set #1

	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9
β_1	0.11	0.10	0.21	0.11	0.79
β_2	0.11	0.00	0.04	0.37	1.47
β_3	0.97	1.15	1.57	1.64	3.46
β_4	0.21	0.10	0.04	0.04	0.01

Ratio of the mean square to the remainder mean square on Set #2

	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9
β_1	1.00	0.16	0.25	0.06	2.45
β_2	1.00	0.16	0.03	0.53	0.27
β_3	1.00	1.42	2.27	7.18	22.09
β_4	1.00	0.16	0.03	0.53	0.27

5.1 Discussion

The above data indicated the most significant contributor to the number of failures was the number of layers on the circuit board, or the dielectric thickness. The boards with more layers, and therefore less dielectric thickness between the layers, generated more failures when the number of heat cycles increased. The data also indicated that as the number of rework cycles increased the dielectric thickness became more significant. The data showed the significance of the other variables was minimal and almost equal.

6.0 Finite Element Analysis

6.1 Purpose

The purpose of this analysis is to determine the stresses for four and ten layer PWAs to demonstrate how the different number of layers effects the reliability of the PTHs.

6.2 Background

Code 312 of Goddard Space Flight Center (GSFC) performed an experiment on PTHs to determine the most significant factor effecting the reliability of the PTHs during soldering rework. Statistical analysis of the experimental data clearly showed that as the number of layers increased, the rate of failure increased PTHs. To confirm experimental data, finite element analysis (FEA) was performed to ascertain how the four and ten layer PTHs behaved under thermal stress. The results of the analysis are outlined in this section.

6.3 Assumptions

A. The thickness of the printed wiring board: 88 mils (2.24 mm)
B. Copper trace thickness: 1 oz/ft2 (0.034 mm).
C. The soldering iron temperature: 600 ?F (315.56 ?C).
D. The temperature of the PTH is in equilibrium with the soldering iron temperature.
E. The stress free temperature was assumed to be 23? C for all materials.

6.4 Loads and Boundary Conditions

The following boundary conditions were used in the analysis:
A. The PTH equilibrium temperature is 600°F (315°C).
B. The bottom of the substrate was restrained from moving in the Z direction (vertical direction) with rotations fixed about the other two axes.

6.5 Materials

Table 1 describes the materials used in the model and Table 2 lists all the material properties. Material properties for the laminate and copper trace are from "Handbook of Electronic Packaging", edited by Michael Pecht[2].

Table 1

Configuration	Material
Lamination	FR-4
Trace	Copper
Barrel	Copper
PTH	Copper

Table 2

Property/Material	Copper	FR-4
Young's Modulus (psi)	16.983E6	2.4968E6

[2]Pecht, Michael, "Handbook of Electronic Package Design", Marcel Dekker, Inc., 1993.

Thermal Expansion Coefficient (in/in°C)	16.7E-6	14E-6

6.6 Results

Maximum thermally induced stresses on PTHs for ten and four layer PWBs were calculated to be 16,092 psi (110.9 MPa) and 13,698 psi (94.4 MPa) respectively. (See Figures 1 & 2.) The ten layer PWB imposed greater thermal stress on the PTH. This stress is the direct result of the thermal mismatch between copper from the barrel and trace with the dielectric material.

6.7 Conclusions

The results of the finite element analysis confirmed Code 312's findings on the significance of the number of layers to effect the failure of the PTH when reworked. The PTH on the ten layer PWB which has more stress than the PTH on the four layer PWB, would have a higher failure rate based on the comparison of thermally induced stresses.